DESIGN OF NATURAL WARNING SOUNDS

Pernilla Ulfvengren

KTH, The Royal Institute of Technology
School of Industrial Engineering and Management
Division of Industrial work science
Stockholm, Sweden
pernillaulfvengren@indek.kth.se

ABSTRACT

The goal of this research is increased safety and human performance in aviation. Human errors are often consequences of actions brought about by poor design. The pilot communicates with the aircraft system through an interface in cockpit. In an alerting situation this interface includes an auditory alerting system. Pilots complain that they may be both disturbed and annoyed of alerts, which may affect performance, especially in non-normal situations when the mental workload is high.

This research is based on theories in human factors /ergonomics and cognitive engineering with the assumption that improved human performance within a system increase safety. Cognitive engineering is a design philosophy for reducing the effort required by cognitive functions by changing the technical interface, which may lead to improved performance.

Knowledge of human abilities and limitations and multidisciplinary interrelated theories between humans, sounds and warnings are integrated into this research. Several methods are included, such as literature studies, field studies, controlled experiments and simulations with pilots.

This research provides design requirements for sounds appropriate as auditory alerts, defined as Natural Warning Sounds. These sounds either have a natural meaning within the user's context, or are compatible with the human's natural auditory information process, or both, they are also pleasant to listen to (not annoying), easy to learn and clearly audible.

In an experimental study *associability* of different sounds were compared. Associability is the required effort to associate sounds to their assigned alert function meaning. The more associable a sound is it requires less effort and fewer cognitive resources. The study shows that auditory icons and animal sounds were more associable than conventional alerts!

In another listening study the method of Soundimagery was used to develop soundimages. A soundimage is a sound, which by its acoustics characteristics has a particular meaning to someone without prior training in a certain context. Soundimages were successfully developed, however it may be difficult to come up with sound candidates for functions that lack sound or are not associated to a particular sound.

In a simulation study different presentation formats were compared. The results show that auditory systems should have cancellation capabilities and avoid continuously repeated alerts.

This research brings related theories closer to practice and demonstrates methods that will allow designers, together with the users of the system, to apply them in their own system design.

[Keywords: design requirements, auditory warnings]

1. INTRODUCTION

Aviation is a very safe transportation system. However, despite the fact that air traffic has not become any less safe, the number of headlines with accidents becomes more frequent due to both increased air traffic and media coverage across the world. Every time there is a headline, even without casualties, airlines experience a loss of passengers and money [1]. Civil aviation authorities set higher safety goals, for safety and efficiency.

Human errors are said to be responsible for 60-80% of all accidents [2]. In aviation the pilots are commonly pointed out and statistics from 1956-1996 ascribe 73.3% of the accidents to the cockpit crew [1]. Errors causing accidents can many times be traced back to many causes of which the operator's error only happened to be the last or *active error* in a trajectory of events [3]. The point is that human errors often are consequences of actions brought about by poor interfaces and system induced errors or surprises [4][5][6].

In the cockpit the pilot is quite isolated away from the aircraft systems. All communication with the system is carried out through a human-machine interface usually displays and control panels. The pilot crews have a good presentation on their displays of the aircraft system status, navigational position and predicted flight path in normal situations, but the use of alerts and warnings is necessary in providing relevant information in a non-normal situation. Through the interface visual information as text, symbols, lights and audio information as signals, voice messages, as well as tactile stimuli are presented and must provide good communication between the pilot and the aircraft. Their main purpose is to alert, inform and guide the pilot, in this order [7].

In December 1991 an aircraft accident occurred in Sweden. An MD-80 lost the power of both engines at low altitude only 77 seconds after take off. All 123 passengers survived the crash landing. The accident was analyzed from a human factors perspective [8][9]. The loss of power resulted in many consecutive failures.

"One of many alerts heard was the autopilot disconnect and Ground Proximity Warning System (GPWS) signaling *whoop-whoop-terrain* and *whoop-whoop-pull-up*. Coming through the clouds 15 seconds before impact, the pilots knew it was only basic flying left. They even told the air traffic controller, -We are crashing to the ground... The *GPWS* still advised *terrain-whoop-whoop-pull-up* over and over again. It continued to do so until they hit the ground… "[8].

In an alerting situation like this one, "all the lamps are blinking and there are a lot of warning sounds in the cockpit. It is really a terrible environment“ [8]. It stood clear that the pilots had been overloaded with information, and the auditory alerts contributed to this, repeatedly sounded all the way down to impact.

Problems identified with alerting systems formed the base for a research project in which interviews with pilots for various commercial airplanes were conducted [10]. It was found that pilots in a warning situation with multiple failures were discontent with the presentation of auditory warnings. Some of the comments by pilots in these interviews were:

- So many aural signals may be confusing.
- Can't separate the sounds, do not like voices.
- Pling-plong, meaningless!
- Chime and horn difficult to separate.
- Been confused.
- Aural warning may aggravate the work load.
- Very distracting sound.
- It would be good to be able to turn the sound off so one could think.
- Imagine lots of voices during take-off or landing, terrible.
- SELCALL during critical landing, made me unintelligent.
- Can't hear radio traffic for all the sounds.
- Turn off sounds or at least minimize duration!
- Fire alarm too high intensity.
- Stick shaker and over-speed at the same time... no inhibitor.
- Auto-pilot disconnect, you forget to push a second time.

These comments can be related to different issues in auditory alert design, mainly; the type and number of sounds (meaning, confusion, distraction), presentation format and system logic (prioritization, cancellation, duration, intensity). Most comments above describe the combined problem of sound and system design.

It should be remembered that it might not always be the sounds themselves but the total amount of visually/auditory presented information and combination of these that the complaints are based upon. Commonly stated issues are still that auditory alerts are too many, too loud, they need to be learnt, they are not mapped between urgency and the alerting situation, and they are easily confused among each other [11][12][13][14][15][16].

Traditionally sounds have been assigned arbitrarily and the pilots have had to learn their meaning and consequently recalled them in memory when heard. A failure or malfunction situation is rare and some alerts are therefore seldom heard. This might also contribute to memory demands on the pilots if the alerts are not obvious or easily recognized. When an auditory alerting system has poor design it gives little information or guidance, which contributes to extensive workload for the operator, especially in a non-normal situation.

With an improved design auditory alerts even have the potential to alert as well as to inform and guide the pilot without the pilot having to look down or change visual focus from an ongoing task. This increases the time possibly spent flying head-up plus enhances the performance in cases of low visibility and at other visually demanding times and should contribute to increased safety [14][17][18]. In non-normal situations there is generally an increase of communication among the pilots as well as between the pilots and both the aircraft and ground. This communication could be improved with a better auditory alerting system and this could also contribute to better performance and safety.

In older airplanes there were fewer alerting functions. Not all of them had auditory alerts but each alert had a unique sound. When automation and complexity increased, the number of functions increased. The alert sounds for these functions consequently increased too and were found to be hard to remember and discriminate among each other [14][19]. For many years the aircraft industry made an effort to reduce the number of alarms in the cockpit so as to avoid information overload. One airframe manufacturer has managed to consolidate systems warnings down to two signals, which differ in two levels of urgency, instead of having an individual sound assigned to each function. This means that the only function of the sound is to alert the pilot. To inform or guide the pilot is left to the visual display to do.

The two auditory signals for warning and caution are despite the design intent of the manufacturer still not the only auditory alerts in the final aircraft. Flight parameter auditory alerts are still in use and regulations from authorities require additional systems with auditory alerts. These are stand-alone alerting systems added after the aircraft has been manufactured. See more in a review of different design and design philosophies of alerting systems across commercial airplane types and manufacturers [10].

1.1. Purpose

The overall goal of this research is increased safety in aviation. This research is based on theories in human factors and ergonomics with the assumption that improved human performance within these systems increase safety.

Furthermore, cognitive engineering, minimizing cognitive effort for the pilots through a better human-machine interface design increases their feeling of directness to the system as well as increases the overall system performance [20][21].

The *aims* of this research have been:

- To describe properties of sound necessary for efficient auditory alerts.
- To suggest in which format the auditory alerts should be presented.
- To suggest a design process that can be used for design of auditory alerting systems.

The first aim relates to the cognitive component such as information representations and content and the second aim to the physical components including size and shape of the alerts for example repetition rate and amplitude.

2. METHODS

Human factors and ergonomics are applied in this research. Specific for this field is the interplay of basic and applied research. There is also interplay between descriptive and experimental methods in collecting empirical data. Descriptive methods used in this research are mainly interviews and questionnaires.

Several methods are involved in this research; literature studies, field studies with studies of current designs, controlled experiments and evaluation, review of standards, guidelines and requirements definition and simulations with pilots. For more detailed description of methods and experimental design, see references for each particular study [22].

This research is user-centered in the sense of including expertise experiences from pilots in defining the problem and using pilots in finding solutions to the problem for example in the listening studies.

3. RESULTS

A summary of this research main studies are presented below including; literature review, field studies, experiments, and simulation.

3.1. Literature review

A first step to find explanations and possible solutions is discussed in an extensive literature review by Ulfvengren [23] including theories of perception of sound and mainly theories related to identification and classification of sounds, pattern recognition and the effect this might have on learning and ability to discriminate among alerts.

It is concluded that a feasible area of improvement in auditory warning design is the type of sounds used. They need to have more meaning for the pilots in their context. Natural speech and other complex sounds with irregular temporal characteristics are possibly more suitable than other more abstract sounds, and should be more easily learned and discriminated from others.

Humans use sounds, gestures and symbols to refer to objects and concepts by *representation*. "The power of cognition comes from abstraction and representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details" [24]. Representation is essential in any auditory interface.

The concept of *affordances* explains what the environment affords us. "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or for ill" [25]. The word *affordances* was coined by Gibson and means in other words direct perception of meaning. Gibson gives an example of a surface that is horizontal, rigid and big enough that it affords support, i.e. it is stand-on-able. This theory is also used in other contexts of design [26][27]. Stanton and Edworthy [28] use the term auditory affordances. The idea of is that a sound is perceived correctly if it sounds like what it is.

Another important issue is that "it is never necessary to distinguish *all* the features of an object and, in fact, it would be impossible to do so. Perception is economical" [25]. It is important to distinguish which features that are relevant and critical in an auditory interface. It is not necessary that all aspects of a sound can be found in a natural surrounding, but that its critical features can.

Alerts should communicate relevant *Perceived Urgency*. A definition of the alerting qualities or perceived urgency in a sound is "to know the relative alerting qualities of iconic stimuli in order to provide at least a rudimentary mapping between the risk we are portraying, and the warnings which are portraying them" [29].

Sound without source and source without sound. In a real application setting such as a flight deck, some functions may have a true source of sound and some may not. For example the use of *auditory icons* [30] is splendid, but, what is the auditory icon of an alert of high altitude? What does it sound like? Another problem can be that the surrounding noise might mask the sound and make it rather useless or that it lacks appropriate level of urgency. It is therefore necessary to look at ways to find appropriate sounds also for these cases!

In a classic paper, "The magical number seven" [31] channel capacity of one-dimensional stimuli judgements is discussed. However, what is also discussed is the possible enhancement of the channel capacity with multi-dimensional stimuli. For one-dimensional auditory stimuli the channel capacity levels out with seven tones. But in another experiment tones with "frequency, intensity, rate of interruption, on-time fraction, total duration and spatial location" were variables. The study included 15625 different tones. Instead of the magical 7, now 150 different categories could be absolutely identified without error. This implies that the complexity of sounds have implications on confusion among alerts.

A pure tone is a meaningless sound. *Meaningful sounds* vary in many more ways than merely in pitch, loudness and duration. Instead of simple duration, "they vary in abruptness of beginning and ending, in repetitiveness, in rate, in regularity of rate, or rhythm, and in other subtleties of sequence. Instead of simple pitch, they vary in timbre or tone quality, in combinations of tone quality, and in changes of all in time…it is just these variables that are distinguished naturally by an auditory system. Moreover, it is just these variables that are specific to the source of sound…" [32]. So, it should come as no surprise to us when a pilot utters "Pling-plong, meaningless!" [10].

3.2. Examples of current alert designs and standards

Current designs of existing auditory alerting systems were analyzed in three different settings. These were an intensive care unit, a full-scale nuclear power plant simulator and an aircraft.

It was found that auditory alerts are necessary in these types of complex systems and that they have the potential of increasing safety and performance. However, it was also found that despite the great need for, potential of, and good intentions with auditory alerts, the current design do not fulfill the requirements of the standards.

Common advantages and disadvantages with current designs were found between the systems. The disadvantages were that auditory alerting systems *waste the resources* of the operator's cognitive resources. Complaints were made about alerts that are difficult to identify among others since they were not possible to discriminate or lacked meaning or both.

Auditory alerts may sound continuously and are not cancelled even if the operator already has received the intended information. These alerts are second-hand or *used auditory alerts*, since they are no longer useful to the operator. Most aircraft today have inhibitors or automatic cancellations for those alarms, others have a manual switch [10]. At the intensive care unit a nurse responded "Ah, that button is the cancellation button. It is used so much the text has worn off!", when asked about a button without labeling

This may be considered in any time-critical situation when time or thought perhaps should not be wasted on trying to find the cancellation button or even to think of it.

Complaints are also made about loud, distracting sounds, false alarms and the nuisance that some alarms require manual cancellation.

3.2.1. Alert design examples

There were some designs of the auditory alerts of special interest.

Hospital equipment:

Propaq was a brand of a helicopter certified equipment for heart activity. The alert was very soft and high pitched. It did not seem appropriate for the noise environment in a helicopter. Complaints were expressed that it was extremely hard to hear.

DATEX was a very much liked integrated alerting system which had a good visual and auditory display. The personnel could choose the sound configuration. When the criticality increased the sound changed to a higher perceived urgency. It was repeated with intervals that allow the personnel to react on the alarm before it was repeated.

A mattress used for keeping the body temperature for patients undergoing surgery had an alarm that was activated when the mattress temperature exceeded 37^{o} C, which is not a critical temperature! The alarm was perceived more urgent than that for cardiac arrest!

Non-verbal warnings are almost always preferred before speech messages since patients might become uncomfortable and worried in hearing certain information.

Nuclear power plant alerts:

There are two sounds that are most frequently used, the first hierarchy level is called the *pling-plong* and known by everyone at the plant. To find out exactly what has caused the alarm, the operator seeks for information on the visual display. If it is not attended within 10 seconds the second level goes off and is called *the war is coming*! This is the second level hierarchy level and higher priority alert. All alarms use the same two alerting sounds and if several values change in different systems there will be an overlap of several *pling-plong* alarms and maybe even a mix with *the war is coming*. There is another additional system, which also have similar *pling-plong* and *the war is coming* alerts.

3.2.2. Review of standards and guidelines

This study also included a review of guidelines and standards in the field of auditory alerts [23][33].

International standards were reviewed, such as; ISO 9703-2 for Anesthesia and respiratory care alarm signals, ISO/DIS 11429 Ergonomics-system of danger and non-danger signals with sound and light, MIL-STD 411F for Aircrew Station Alerting Systems and DOT/FAA/RD-81/38 II the FAA Crew alerting guidelines.

In ISO 9703-2 it states that auditory alerts should provide "maximum transmission of information at the lowest practicable sound pressure level, ease of learning and retention by operators and perceived urgency".

In ISO/DIS 11429 the general requirement on an auditory alert is to invite to rapid and correct recognition under difficult conditions.

In 1982, Patterson published a CAA report "Guidelines for Auditory Warning Systems on Civil Aircraft"[14]. This report discusses guidelines for: overall sound level, temporal and spectral characteristics, ergonomics of auditory warnings and voice warnings.

FAA Crew alerting guidelines, DOT/FAA/RD-81/38 II, states that aural alerting sound should: attract attention and provide preliminary indication of urgency, be kept to a minimum, always appear in conjunction with visual display and minimize demands on crew information processing and memory.

The existing standards and guidelines say little of *how* to accomplish the recommended design of appropriate sounds and their presentation format, which may be one reason of why so little of these guidelines are applied in existing systems. Most guidelines are very general. For example: that alerts *should minimize demands on crew information processing and memory* (DOT/FAA/RD-81/38 II).

In conclusion there is much room for improvements in auditory alerting systems and more research is needed to develop guidelines and methods for design of appropriate sounds and their presentation format for future systems.

3.3. Associability study

In the results from the literature studies ideas that different properties of sounds effect required cognitive resources are presented and based on theories and theses ideas experimental studies were performed [34] to learn more of different efforts required by different sounds associated to an alert function.

The concept of *associability* represents the required effort to associate sounds to their assigned alert function meaning. If a sound is possible to associate, *associable*, to a given alert function it requires fewer cognitive resources and is therefore appropriate, in this aspect, for auditory alert design. More associable sounds are also less confusing, faster identified, easier learnt and remembered than less associable sounds and sounds that are simply not associable.

The idea was to test which *sounds that are easy to associate to a function* and which were not. The intention was not to see which sounds that were easily identified as in earlier psychoacoustics approaches. Because in a real application setting such as a flight deck there are already known alerting functions for which auditory alerts are sought. When designing auditory alerts it is difficult to know which sounds that would make efficient alerts for these alert functions. Associability studies aim to bring light to these issues.

In these experiments different categories of sounds were compared with respect to how many learning trials that were required in order to learn to associate 10 sound-meaning (or alert-alert function) pairs. The meanings that were paired to the different sounds were a set of alert functions from an automobile setting for example; low fuel, seat belt, dim head lights.

The experiments were conducted to show that the choice of sounds used as auditory alerts have an impact on several perceptual and cognitive issues. Humans can easily identify hundreds of sounds in normal environment but our ability to learn abstract unknown sounds is very limited, which implies it may not be the amount of sounds as much as wrong sounds in existing systems. Another idea that was tested was to use known, familiar easily identified sounds intentionally in a new context. As one category in this study animal sounds were paired with alert functions. For example the *sound of a pig* was given the alert meaning *low fuel*.

The sound categories chosen for the study differed in properties such as: Type of sound; environmental, ecological, synthetic tone patterns, arbitrary tones and signals. They represent the source of sound at different levels of abstraction; abstract, semi-abstract and representational. They are either intentional or incidental. The sound categories included in the studies were; auditory icons, animal sounds, attensons, conventional auditory alerts and natural speech.

It was predicted that unknown abstract sounds such as conventional alerts would be less associable than complex environmental sounds such as auditory icons. It was also predicted that the attensons, being more complex than conventional alerts, would be more associable than these. Two speech categories were also included but they were considered as a base line and required no learning.

The main results were (see figure 1):

- The auditory alerts which have sounds that own properties related to the alert function, auditory icons, were proven better than all the other sounds.
- Surprisingly the Patterson's attensons [14] were showed to be more confused and difficult to discriminate than conventional alerts from existing aircraft and rotorcraft.
- Familiar sounds and easily identified sounds, such as animals, used as alerts in a completely different context were proven to be easier to learn than both the existing alerts and the attensons.

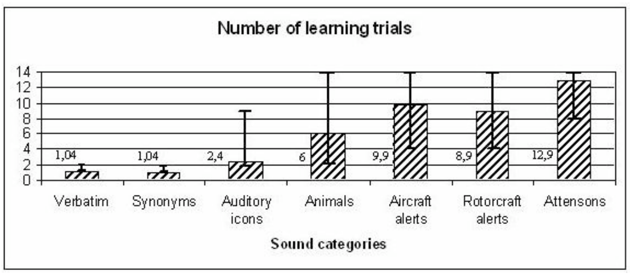

Figure 1. *There was a statistically significant difference among the categories. Auditory icons required more learning trials (p<0.05) than speech. Animal sounds were easier to learn (p<0.05) than alerts and attensons. Attensons were more difficult to learn than all the other categories (p<0.05). Source, figure 2 in [34]*

This study shows that some sounds type require fewer cognitive resources than others both in a learning task and in a retention task. Associability is therefore an important aspect in auditory alerting systems design according to cognitive engineering.

3.4. Soundimagery study

In the associability study auditory icons which own properties related to the alert function had highest associability. In a user-centered approach the experts that best could identify those properties are pilots. The way a sound is associated to a meaning is dependent of the listener's experiences of sounds and in which context sounds have been heard.

In this study [35] the method of soundimagery [36] was used in listening studies with helicopter pilots. A soundimage is a sound, which by its acoustics characteristics has a particular meaning to someone without prior training. Soundimages are not restricted to any category of sound.

When good soundimages are found they need no learning, they have an intrinsic meaning to the pilots in their context. In terms of associability Soundimages are highly associable sounds and believed to require the least cognitive resources of all alerts.

Soundimages may come from any possible category of sounds. In the sample of sounds played to the pilots near to all existing alerts in aircrafts were included together with new sounds from many other categories of sounds. Some of these existing alert sounds got high ratings and some were not associated to their existing function at all! It should be mentioned that some alerts that could be considered as abstract sounds by novices were considered by experienced pilots to be good soundimages. These sounds have by long use become near to environmental in the cockpit setting.

The pilots were well familiar with the alerting functions used in the studies. They were presented to a various number of sounds, both existing alert sounds from rotorcrafts known to the pilots and sounds from different contexts, which the pilots may, or may not, know.

The pilots assign sounds to alert functions after their preferences, which results in a sound receiving a number of votes. They choose the sound they associate most to a particular alert and they also rate how well they think the sound represents this alert function.

These screening studies [35] show that pilots agree significantly on sound-meaning pairs. For a sound to be selected for implementation it must meet the three criterion; number of votes, soundimagery ratings and confusion. If several sounds are paired with one function and only for this function, the sounds might all be good soundimages. If these sounds are chosen there is little risk of confusion. However, confusion occurs when a sound is associated with more than one function.

In discussions with pilots it is understood that both context and urgency of the alert is part of their ratings. The soundimagery method was clearly sufficient and pilots found it easy to use.

The use of soundimagery in developing alerts may improve crew response and give relevant information in a timely manner as well as reduce cognitive workload during actual flight operations as well as decrease pilot training in upgrades or new models.

If no good soundimages are found and a sound still will need to be assigned to a meaning it will need to be learnt. The results from the associability studies can be used to minimize this training and used as a complement to soundimagery.

3.5. Presentation format simulation

Many aircraft alerts are presented continuously repeated. The pilots are to make difficult decisions and act as well as communicate in this environment. This has not been subject to extensive research with pilots.

The purpose with this study was to obtain judgments about proposed future systems from pilots. Both voice messages and sound alerts were used. The variables were number of repetitions and cancellation capability of the alerts.

In this study [37] data was collected from helicopter pilots in a part task simulator. The study was designed to investigate pilot/aircraft performance and pilot ratings of utility as a function of the presentation logic of auditory alerts.

The experimental conditions were continuous presentation of alerts with and without cancellation capabilities and self-cancellation after one, two and three repetitions. Duration and interval was held constant. The pilots flew different missions in the helicopter simulator. Each mission had a different configuration of the audio alerting system. After each mission the pilot completed a questionnaire regarding that alerting system configuration. They also completed a questionnaire for the study as a whole.

Main results from this study were that:

- All pilots preferred to be able to cancel the audio alerts when they were presented continuously.
- Pilots rated number of repetitions after each mission. There was a large spread in the data and their chosen preference of configuration was often situation dependent.
- Continuous alerts were rated too many as well as distracting and interrupting in problem solving tasks and communication.
- Continuous alerts with cancellation capabilities was considered just right and allowed pilots to control the number of repetitions.

The most preferred number of repetitions of alerts was in many cases situation dependent. The pilots in this study suggested a system, which allows for a flexible presentation with three repetitions, which allow for a backup after a pause just in case all three were missed. The pause is there to allow for decision-making and action and perhaps to cancel the alert without ongoing repetitions of alerts, which is very annoying.

3.6. Design process

The design processes of both human factors engineering and ergonomics are iterative, involving repeated cycles of design and evaluation, starting with formulating the problem and then designing an appropriate solution and developing it to perform well and assuring user satisfaction [38][39].

A human-centered design process: starts with the need of the user, requires understanding and specification of the context as well as organizational and user requirements. The design initially use prototypes which are evaluated according to goals and requirements specified. Iterative modifications are possible before the design fulfill goals and requirements.

An attempt has been made to develop a user-centered design process for auditory warnings [40]. It is based upon an existing international standardized method for evaluating public information systems (ISO/DIS 7001: 1979). The effectiveness of this design method had at the time not yet been tested in practice [40]. A user-centered approach allows the user to have some input into the design of the warnings.

The adapted process includes stages as; *establish the need for warning* for given referent functions, include *existing and modified sounds* as well as *new trial sounds*, run an *appropriate ranking test* of the sounds, *design trial warning set* based upon the results so far, a *learning and confusion* test will show if alerts within a set will be confused perhaps because of similarity of sounds or function, *urgency mapping* test will make sure the mapping between the signal and situation is appropriate in terms of urgency, *design prototype warning set*, do a follow-up *recognition and matching test* where simply respondents hear sounds and are asked to map these to appropriate warning function, *generate standardized verbal description* both in verbal descriptions of type of sound and a more *acoustical description* that would allow reproduction of the sounds and finally an *operational test* in a realistic setting.

This research suggests in addition to this a cognitive engineering design process that includes the methods of associability and soundimagery, figure 2. This design process is believed to result in an auditory alerting system with Natural Warning Sounds with an appropriate presentation format.

4. DISCUSSION AND CONCLUSIONS

In this research, on one hand, a human and ecological approach has been taken. *Natural sounds* in that approach are sounds found in our natural environment which are believed to be most compatible with our auditory information process. On the other hand, a user approach has been taken. Sounds that pilots have experienced and learned in aviation is *natural* to them in this context. Since this is an artificial environment some sounds are not natural in the sense that they can be found in the natural environment in which our hearing evolved. These sounds may even be acoustically *unnatural*, simple and one-dimensional sounds not found in nature. They are only meaningful to pilots.

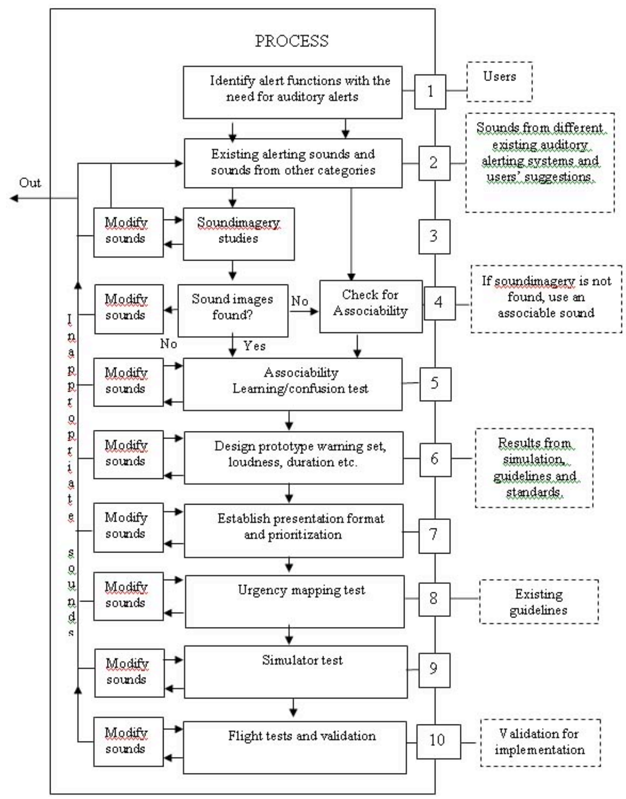

Figure 2. *A cognitive engineering design process for Natural Warning Sounds and auditory alerting systems.*

This argument means that there should be no restrictions in the sounds tested for auditory alerting systems design.

The term natural warning sounds should not to be connected to an ancient animal which our ancestors feared and natural warning sounds are not necessarily heard during an aircraft accident. Even though there might still be advantages in those cases where truly ecological sounds coincide with a chosen auditory alert there might still be enough advantages to choose a familiar one-frequency beep for some alerts. In the concept of natural warning sounds the interpretation of *natural* includes sounds that are natural for the pilots in their everyday environment. The appropriate properties and design requirements for an efficient auditory alert are natural warning sounds, either from a human view, or a user view, and preferably both.

It is believed that the methods presented in this research are general of their kind and defined by the user and the user context. Therefore the design process suggested can be applied to any human-machine system, for example: cars, hospital equipment, intelligent homes application and mobile phones.

The *first aim* of this research has been to describe the properties of sounds appropriate for an auditory alerting system. The sounds should meet the following requirements for natural warning sounds:

- Have a natural meaning within the user's context,
- Be compatible with the auditory information process,
- Be pleasant to listen to (not annoying),
- Be easy to learn,
- Be easy to remember,
- Be efficient for action,
- Be efficient for compliance,
- Decrease time for performing the task,
- Contain relevant information,
- Be clearly audible,
- Be easy to discriminate from other groups of alerts,
- Be easy to discriminate from other individual alerts.

The *second aim* of this research has been to suggest in which format the auditory alerts should be presented. Important issues were identified and the knowledge gained during the analyses of existing alerting systems and performed simulations as well as theoretical results, are valuable for the process of designing a warning system.

The *third aim* of this research has been to suggest an improved design process for auditory alerting systems by applying cognitive engineering to a user-centered design process including the methods of associability and soundimagery.

The *overall goal* of this research is increased safety in aviation. This research have to rely on theoretical and experimental results and prove by logical arguments that natural warning sounds and suggested presentation format are predicted to increase overall system performance and safety.

This research has demonstrated general methods that will allow designers, together with the users of the system, to apply these in design in their own system.

4.1. Future research

In future research there is a need to study methods to assure that the sounds are highly associable among other alerts. In a set of similar associable sounds, an unfamiliar abstract sound may stick out and be very easily associated to any other function due to high contrast. Associability tests with groups of sounds from a various mix of categories of sounds should be tested.

One issue that has not been discussed in this research are alerts that are designed to give direct feedback, for example the stall warning. It goes off when the aircraft is stalling and silence when the stall is recovered. As long as the stall is possible to recover from immediately the duration of the alert is meaningful, however it might be distracting in other situations. This tradeoff of such an alert design needs to be studied, possibly together with the turn-off threshold.

Research needs to obtain results for a turn-off threshold [29] to develop guidelines or methods to obtain appropriate repetition rates and cancellation capabilities.

Further studies of understanding critical features of soundimages or reasons for the pilots to choose certain sounds should be performed to learn more of sounds and to improve selection of prototype sounds.

Theories and earlier research of warning system logic and integration of different alerts as well as prioritisation of warnings have only briefly been mentioned. This is a large area with much potential to improve the alarm problem.

Further experiments are needed to complement and validate the suggested design process. For example a full set of auditory alerts based on associability studies and soundimagery need to be developed and tested in a more extended simulation.

5. REFERENCES

[1] Graeber, C (1998) Plenary speech *Proceedings of the 2nd PECE conference*, Oxford.

[2] Perrow, C. (1984) *Normal Accidents: Living with high-risk technologies.* New York. Basic Books.

[3] Reason, J. (1990) *Human Error*, Camebridge University Press, New York. ISBN 0-521-31419-4.

[4] Wiener E.L. (1977) Controlled Flight into terrain accidents. System-induced errors, *Human Factors*, **19**, 171-181.

[5] Sarter N.B., and Woods D.D. (1992) Pilot Interaction with cockpit automation: Operational experiences with the flight management system, *International journal of aviation psychology*, **2**, 303-321.

[6] Sarter N.B., and Woods D.D. (1994) Pilot Interaction with cockpit automation II: An experimental study of pilots' model and awareness of the flight management and guidance system, *International Journal of Aviation Psychology*, **4** (1) 1-28.

[7] Hawkins, F.H. (1987) *Human Factors in Flight*, 2nd edition, Orlady, H.W (Ed.) Ashgate, USA.

[8] Mårtensson, L. (1995) Requirements on work organisation, - from work- environment design of "Steelworks 80" to Human- Machine Analysis of the Aircraft Accident at Gottröra, *Doctoral Thesis*, KTH, ISSN 1104-2656.

[9] Mårtensson, L. (1995b) The aircraft accident at Gottröra- the experiences of the cockpit crew, *The International Journal of Aviation Psychology*, **5** (3), 305-326.

[10] Mårtensson, L. and Singer, G. (1998) Warning Systems in Commercial Aircraft- an analysis of Existing Systems, *KTH Report*, Stockholm, ISRN KTH/IEO/R-98/1-SE.

[11] Edworthy, J. (1994) The design and implementation of non-verbal auditory warnings, *Applied Ergonomics*, **25** (4), 202-210.

[12] Haas, E.C. (1995) The perceived urgency and detection time of multi-tone and frequency-modulated warning signals in broadband noise, *Doctoral thesis*, Virginia Polytechnic Institute and State University.

[13] Noyes, J.M., Starr, A.F., Frankish, C.R. & Rankin, J.A., (1995) Aircraft warning systems: application of model-based reasoning techniques, *Ergonomics*, **38**, (11), pp 2432-2445.

[14] Patterson, R.D. (1982) Guidelines for Auditory Warning Systems on Civil Aircraft, *CAA Paper 82017*, ISBN 0-86039-174-4.

[15] Simpson, C.A. (1997) Integrated warning, caution, and advisory (IWCA): A design concept for cockpit alerting

systems. *In proceedings of International Ergonomic Association 13th triennial congress,* Tampere, Finland.

[16] Stanton, N. and Edworthy, J. (1999) *Human Factors in Auditory Warnings*. ISBN 0-291-39849-9, Ashgate.

[17] Edworthy, J., Loxley, S. and Dennis, I. (1991) Improving Auditory Warning Design: Relationship between Warning Sound Parameters and Perceived Urgency, *Human Factors*, **33** (2), 205- 231.

[18] James, S. (1997) Audio warnings for the military cockpit. *Journal of Defense Subnet,* 2:2, UK.

[19] Boucek, (1999) Personal communication at Boeing, Seattle, US.

[20] Norman, D. A. (1986) Cognitive Engineering, Ch. 3 in Draper S.W. and Norman, D.A. (Editors) *UCSD, User-Centered System Design*, Lawrence Erlbaum Ass. ISBN 0-89859-872-9 (PB).

[21] Rasmussen, J. (1986) *Information processing and human-machine interaction: An approach to cognitive engineering*, New York: North-Holland.

[22] Ulfvengren, P. (2003) *Design of Natural Warning Sounds in Human Machine System.* Doctoral thesis, KTH, ISRN/KTH/IEO/R-03/17-SE, ISBN 91-7283-656-3.

[23] Ulfvengren, P. (1999) *Natural warning sounds in safety critical human-machine systems.* Working paper ISRN/KTH/IEO/R-99/08-SE.

[24] Norman, D. A. (1993) Things that make us smart-Defending human attributes in the age of the machine, Addison-Wesley Publ. Company, ISBN 0-210-58129-9.

[25] Gibson, J.J. (1979) *The ecological approach to visual perception*, Boston: Houghton-Mifflin+E138

[26] Norman, D. A. (1988) *Design of everyday things* (Reprint, originally published: *The Psychology of everyday things*) New York Basic books.

[27] Gaver, W.W. (1991) Technology Affordances, in 79-84. Rank Xerox Cambridge Euro, PARC, UK.

[28] Stanton, N. And Edworthy, E. (1998) Auditory affordances in the intensive treatment unit, *Applied Ergonomics*, **29** (5), pp. 389-394.

[29] Edworthy, J. and Adams, A (1996) *Warning Design, A research perspective*, Taylor & Francis, ISBN 07484-0467-8

[30] Gaver, W.W. (1989) The SonicFinder: an interface that uses auditory icons, *Human Computer Interaction*, **4**, 67-94.

[31] Miller, G.A. (1956) The Magical number seven, plus or minus two: Some limits on our capacity for processing information, *Psychological Review*, **63**, (81-97).

[32] Gibson, J.J. (1966) *The senses considered as perceptual systems*, Boston: Houghton-Mifflin.

[33] Ulfvengren, P. (2002) Pilot Study of Three Auditory Alerting Systems. *In Proceedings NES 2002*, Kolmården, Sweden.

[34] Ulfvengren, P. (2003) Associability: A comparison of sounds in a cognitive approach to auditory alert design. Human Factors and Aviation Safety an International Journal, HFAS, 3 (4), 313-331.

[35] Simpson, C.A., Ulfvengren, P. and Gardner, D.R. (2003) Soundimages for cockpit audio alerting and feedback. (*Unpublished manuscript)*.

[36] Simpson, C.A. and Gardner, D.R. (1998) Soundimage for IDM message receipt. Evaluation of candidate soundimages for audio alerting and feedback in the apache longbow (AH-64D) helicopter. Final report. Study performed for US Army Project Manager Apache Longbow.

[37] Ulfvengren, P., Simpson, C.A. and Gardner, D.R. (2003) Simulations of Auditory Alerts Presentations. In Design of Natural Warning Sounds in Human Machine System. Doctoral thesis, KTH, ISRN/KTH/IEO/R-03/17-SE, ISBN 91-7283-656-3.

[38] Rouse, W.B. (1991) Design for success- A Human-Centered Approach To Designing Successful Products and Systems, John Wiley & Sons Inc. ISBN 0-471-52483-2.

[39] Wickens, C.D. and Hollands J.G. (2000) *Engineering Psychology and Human Performance*, 3rd Ed. Prentice-Hall Inc., New Jersey. ISBN 0-321-04711-7.

[40] Edworthy, J. and Stanton, N. (1995) A user-centered approach to the design and evaluation of auditory warning signals: 1, Methodology, *Ergonomics*, **38** (11), 2262-2280.